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HYPER SUPRIME-CAMERA SURVEY OF THE AKARI NEP WIDE FIELD

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ABSTRACT

The extragalactic background suggests half the energy generated by stars was reprocessed into the infrared (IR) by dust. At $z \sim 1.3$, 90% of star formation is obscured by dust. To fully understand the cosmic star formation history, it is critical to investigate infrared emission. AKARI has made deep mid-IR observation using its continuous 9-band filters in the NEP field (5.4 deg^2), using $\sim 10\%$ of the entire pointed observations available throughout its lifetime. However, there remain 11,000 AKARI infrared sources undetected with the previous CFHT/Megacam imaging ($r \sim 25.9 \text{ ABmag}$). Redshift and IR luminosity of these sources are unknown. These sources may contribute significantly to the cosmic star-formation rate density (CSFRD). For example, if they all lie at $1 < z < 2$, the CSFRD will be twice as high at the epoch. We are carrying out deep imaging of the NEP field in 5 broad bands (g, r, i, z , and y) using Hyper Suprime-Camera (HSC), which has 1.5 deg field of view in diameter on Subaru 8m telescope. This will provide photometric redshift information, and thereby IR luminosity for the previously-undetected 11,000 faint AKARI IR sources. Combined with AKARI's mid-IR AGN/SF diagnosis, and accurate mid-IR luminosity measurement, this will allow a complete census of cosmic star-formation/AGN accretion history obscured by dust.

Key words: Infrared galaxies, AKARI, Hyper Suprime-Cam

1. UNDETECTED AKARI SOURCES

Nature hides; the more intense star-formation, the more obscured. The extragalactic background suggests at least half the energy generated by stars has been re-processed into the infrared (IR) by dust (Lagache et al., 1999). At $z \sim 1.3$, 90% of star formation is obscured by dust (Le Floch et al., 2005; Goto et al., 2010b). Therefore, a full understanding of the cosmic star formation history inevitably needs an IR perspective.

The AKARI space telescope has performed a deep mid-infrared imaging survey in the NEP region (Lee et al., 2009). We are studying the multi-band data of these mid-IR galaxies as shown in Table 1 (Takagi et al., 2010; Goto et al., 2010b). However, because very dusty objects cannot be detected in the relatively shallow CFHT imaging data ($r < 25.9$ ABmag; Hwang et al., 2007; Jeon et al., 2010; Oi et al., 2014), there remain 11,000 AKARI sources undetected in the optical. As a result, we lack an understanding of the redshift and IR luminosity of these sources, i.e., they have been excluded from the past cosmic star formation history (CSFH) analysis. These sources can change our view of CSFH—if they all lie at $1 < z < 2$, they will *double* the cosmic star formation density at that epoch.

2. UNIQUENESS OF AKARI MID-IR DATA

The AKARI NEP is one of the best fields for this investigation, due to the availability of continuous 9-band mid-IR filters. Spitzer lacks filters between 8 and $24 \mu\text{m}$ (the critical wide gap between IRAC and MIPS, excluding the tiny IRS peak up array at $16 \mu\text{m}$). Similarly WISE also has a wide gap between 4 and $12 \mu\text{m}$ filters. Therefore, no other telescope can provide continuous 9-band photometry in mid-IR wavelength ($2\text{--}24 \mu\text{m}$) in the foreseeable future. AKARI's continuous 9-band photometry works as a low-resolution spectrum, which is critically important for the following key aspects:

- Two physical processes produce the mid-IR emission: hot dust around an AGN, and PAH emission from star-formation. Quantitatively separating these is of fundamental importance. The continuous 9 filters of AKARI have made this possible through precise SED fitting (See examples in Takagi et al., 2010; Karouzos et al., 2014). Importantly, this is independent of extinction.
- Accurately measuring the mid-IR emission line strength (PAH $7.7 \mu\text{m}$) and continuum luminosity.

<http://pkas.kas.org>

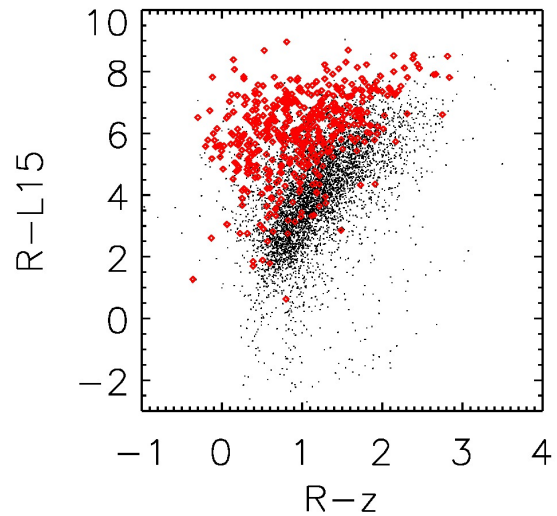


Figure 1. $R - L15$ color is plotted against $R - z$ color. Black dots are AKARI IR galaxies detected with CFHT/Megacam. Red dots are those not detected with CFHT, but with Suprime-Cam in the central NEP deep field.

Using the 9-band photometry as a low-resolution spectrum, Oyama et al. (2014, submitted) demonstrated that photometric PAH $7.7 \mu\text{m}$ line measurements agree well with spectroscopic ones.

Neither of these is possible if there is a large gap between mid-IR filters. Therefore, AKARI NEP is the only field, where the two different astrophysical power sources can be separated for thousands of IR galaxies, including those with heavy extinction.

The AKARI NEP also has been thoroughly observed in every other available waveband (Table 1), making it one of the premier large deep fields on the sky. Its large area overcomes the serious problem of cosmic variance, which hampered previous IR CSFH studies. In particular, Spitzer's CDFS field was only 0.25 deg^2 (Le Floch et al., 2005), and measured an IR luminosity density nearly a factor of 10 different from other Spitzer fields (e.g., Babbedge et al., 2006). For the same reason, the single Suprime-Cam pointing in the center of the NEP deep field (0.25 deg^2) is not wide enough. A large volume coverage also allows us to study environmental effects on galaxy evolution (Koyama et al., 2008; Goto et al., 2010a). AKARI was a survey telescope, which observed 5.4 deg^2 in NEP using $\sim 10\%$ of the entire pointed observations available throughout the lifetime of the mission, providing uniquely precious space-based IR data spanning a large enough area to overcome cosmic variance.

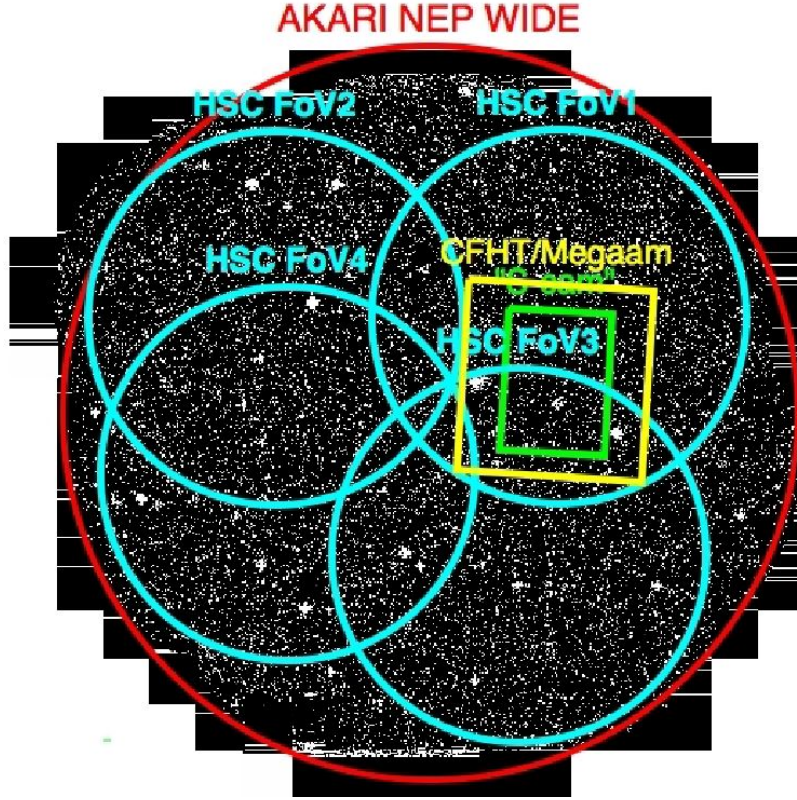


Figure 2. HSC r -band data shown on the background covers the entire NEP wide field (5.4 deg^2). Overlaid cyan circles are planned HSC pointings for the remaining filters (g, r, i, z , and y). Central Suprime-Cam and Megacam fields, where we already have deep optical imaging, are shown in green and yellow.

3. SUBARU HYPER SUPRIME-CAM SURVEY

To rectify the situation, we are carrying out an optical survey of the AKARI NEP wide field using Subaru’s new Hyper Suprime-Cam (HSC; Miyazaki et al., 2012). The HSC has a field-of-view (FoV) of 1.5 deg in diameter, covered with 104 red-sensitive CCDs. It has the largest FoV among optical cameras on an 8m telescope, and can cover the AKARI NEP wide field (5.4 deg^2) with only 4 FoV (Fig.2).

Our immediate science aim of the optical survey is to detect all AKARI sources in the optical, with photometry accurate enough for reliable photometric redshifts. This allows us to determine the optical and IR luminosities (corresponding to direct and dust-obscured emission) from young stars and accreting massive black holes for a large sample representative of the cosmic history of the Universe.

Our main targets—that cannot be detected or measured accurately with smaller telescopes (e.g. CFHT)—are very dusty galaxies with $r - L15 \sim 8$. AKARI’s sensitivity in NEP wide area is $L15=18.5 \text{ ABmag}$ (Lee et al., 2009). Therefore, optical data need to reach $r \sim 26.5 \text{ mag}$. In Fig.1, black dots are bright IR sources

detected with CFHT/Megacam. The red points show colors of AKARI IR sources that can only be detected with 8m depth in the central NEP deep region (Goto et al., 2008). There exist 10 times more of these optically-undetected IR sources in the entire AKARI NEP area (Kim et al., 2012). We derived required deep observations in other bands so that SEDs of Arp220, Mrk231, and M82 (with $L15=18.5$) can be detected at $z=0.5-1$. They are 27.5, 25.5, 24.7, and 24.4 mag in g, i, z , and y , respectively. If we used a 4m telescope, this would take ~ 120 hours in total ($\times 4$ more exposure time, $\times 1.7$ difference in FoV). Therefore, the Subaru/HSC is the only feasible instrument for this observation. Since our targets are heavily obscured, depths in bluer bands are important.

We have abundant spectroscopic data to calibrate photometric redshifts (~ 1000 from Keck/Deimos, and ~ 1000 near-IR spectra from Subaru/FMOS, ~ 1800 from MMT/Hectospec (Shim et al., 2013) as summarized in Table 1. Our experience in the central Suprime-cam field predicts photo- z accuracy of $\frac{\Delta z}{1+z} \sim 0.036$ is achievable from 5-broad band photometry (Oi et al., 2014).

Table 1
Summary of AKARI NEP survey data

Observatory	Band	Sensitivity/Number of objects/exposure time	Area (deg ²)
AKARI/IRC	2.5-24μm	$L15=18.5AB$	5.4
Subaru/S-Cam	$BVRi'z'$	$R=27.4AB$	0.25
Subaru/FOCAS	optical spect.,	57 sources in NEP	$R \sim 24 AB$
MMT6m	optical spec.	~ 1800 obj	5.4
KPNO-2.1m	J, H	21.6, 21.3	5.4
Maidanak 1.5m	B, R, I	$R=23.1$	3.4
KPNO2m/FLAMINGOS	J, H	$J=21.6, H=21.3$	5.4
WIRCAM	Y, J, K	24AB	1
MegaCam	$ugriz$	$r \leq 25.9AB$	1
GALEX	NUV, FUV	NUV=26	1.5
WSRT	20cm	$\sim 100 \mu Jy$	0.25
VLA-archive	10cm	$200 \mu Jy$	5.4
GMRT	610MHz	60-80 μJy	0.25
Keck/Deimos	optical spec.	~ 1000 obj	0.25
Subaru/FMOS	near-IR spec.	~ 700 obj	0.25
Herschel	100, 160 μm	5-10 mJy	0.5
Herschel	250-500 μm	~ 10 mJy	7.1
Chandra	X-ray	30-80ks	0.25
SCUBA2	submm	1mJy	0.25
Subaru/HSC	r	$r=27.2(Fig.2)$	5.4

4. LEGACY VALUE OF THE HSC DATA:

The HSC optical data in the NEP region will have crucial added legacy value. ESA's 1.2m Euclid space telescope (planned launch in 2019), for which several of us are members (T.G., S.S., C.P.), will survey large deep fields to near-IR 26ABmag, with simultaneous near-IR spectroscopy ($R = 250$). These will be exquisite data sets for galaxy/QSO studies to $z=8$ and beyond, and of Type Ia supernovae to $z=1.5$. However, orbital constraints strongly restrict the field choices to within 5 deg of the ecliptic poles. One disadvantage of Euclid is it has only one broad filter in the optical. Therefore, HSC's deep 5 broad-band optical photometry is crucial to compliment the deep near-IR data from Euclid. Without HSC data, Euclid's deep near-IR data will not even have decent photometric redshifts.

Due to similar orbital constraints, the eROSITA space telescope will also have an exceptionally deep X-ray field around the NEP (scheduled launch in 2017). The NEP is also a promising deep field candidate for SPICA, the next generation 2.5m IR space telescope with far-infrared wide-field IFU capability. NASA's JWST will also have excellent NEP visibility. For long-period variable and slow moving objects, taking data at early epoch will only increase the value. Finally, the NEP is also

part of the LOFAR tiered 30,60,120,200MHz extragalactic survey, with a 120MHz $RMS \leq 25 \mu Jy$. The NEP field may not have as rich ancillary data as COSMOS or CDFS at the moment, but it will in the next 10 years, because of its visibility from Space. Therefore, HSC data are not only important for AKARI, but will continue to have a legacy value for at least the next decade.

5. 2014 HSC OBSERVING RUN

Our proposal to the Subaru telescope was accepted with a high score (8.0 out of 10). We were awarded two nights of Subaru time on June 29 and 30, 2014. However due to instrumental problems such as a crash of the instrument control PC, we were only able to observe on June 30, without the filter exchanger, i.e., we were limited to the r -band observation.

Nevertheless, we carried out the observation in r -band. Due to a problem with a dome air control during the daytime, the seeing was 1.5-2.0", while outside seeing was 0.4-0.6". Because the temperature was higher inside the dome (6C vs 4C outside), we tried to open the ventilation windows, knowing this increases the turbulence within the dome. This helped to improve the seeing from 2.0" to 1.5". However, as soon as we closed the ventilation windows, the seeing went back to 2.0". We decided to keep the ventilation windows open for the

rest of the night.

We observed in 7 FoVs with sets of 5 point dithering pattern. Because the largest spatial gaps of the HSC CCDs are $\sim 53''$, we shifted $\sim 120''$ at each dither. This is to ensure to fill CCD gaps and to have enough stars observed in two separate CCDs for calibration purpose. Our dither pattern was designed so that ΔRA , and ΔDEC distributions become random, with no repeated points.

6. DATA REDUCTION

Due to its large size, the reduction of HSC data is a challenge. With the courtesy of the HSC team and NAOJ, we used the HSC pipeline developed by the team. Over 200 GB of data taken in one night, it took 7 days of cputime to reduce and mosaic data with a workstation with dual CPUs (E5-2620-v2 6core, 2.1 Ghz, 24 threads with Hyper Threading Technology in total) and 64GB of memory. Depth varies across the field due to the seeing variation during the night. However, in deepest portions we reached $\sim 27AB$ mag.

7. SUMMARY

We are carrying out deep HSC g, r, i, z , and y imaging of the AKARI NEP wide field (5.4 deg^2). The HSC observations will provide photometric redshifts and thereby IR luminosities for 11,000 faint AKARI IR sources, previously undetected with CFHT. Combined with AKARI's mid-IR AGN/SF diagnosis, and accurate luminosity measurement from the unique 9 mid-IR photometry, this will provide a complete census of the obscured cosmic star-formation/AGN accretion history at high- z , to be compared with the state-of-the-art low- z work also from AKARI (Goto et al., 2011b,a; Kilerci Eser et al., 2014).

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